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Characterizing Fuel Load and Topographic Relationships in a Montane Canyon of Southern Arizona

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Characterizing Fuel Load and Topographic Relationships in a Montane Canyon of Southern Arizona

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Abstract

Pole Bridge Canyon is a Research Natural Area and exemplary montane canyon in the Chiricahua Mountains of Southeastern Arizona. Montane canyons of the Southwest are oases for diverse flora and fauna, and targets for destructive wildfire. We combine a digital elevation model, fine-scale field data and remotely-sensed imagery to examine fuel load complexities among distinctive vegetation types and topographic positions. Digital elevation models (DEM) provide the topographic distributions, representing temperature and precipitation variations that affect productivity and fuel production. DEM data and *in situ* measurements of surface fuels and the forest canopy are used to characterize overall fuel complexity. Multispectral remote sensor data from the Landsat Thematic Mapper (TM) provide spectral information on forest structure and composition. Results show fuel loads are highly heterogeneous and vary at fine spatial scales. Given observed variations in fuel loads, differences in species composition, and the prevalence of a high oak fraction in this sky island region, we suggest consideration be given to creating fire behavior fuel models specific to the desert Southwest.

Keywords: forest fuels, topography, GIS, fire, management, southwest, Arizona, sky island, Landsat Thematic Mapper, TM

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the Mt. Graham International Observatory. Resources brought to this fire included 1100 persons, 26 engines and 9 helicopters. Such events compel fuels mapping and new management initiatives to prevent destruction of large tracts of forests valued for commercial, recreational, natural and scientific uses. A new fire management plan has been proposed for part of the Wilderness not affected by the Rattlesnake fire. This plan aims to reduce high fuel loads that threaten the Chiricahua Wilderness with catastrophic wildfire (Hardy 1998).

Unique Southwest Fuel Complexes

Prescribed natural fire is endorsed increasingly as a means of restoring natural fire regimes to systems with a history of grazing, logging, and fire suppression (USDI, USDA 1996; Ffolliott, et. al, 1996; Sackett, et. al, 1996). Restoring natural fire cycles to systems no longer natural appears, however, improbable (Allen 1994; Fflolliot 1996). Prior fire research focused primarily on the timber regions of the Rocky Mountains and Pacific Northwest. Faced with field observations we report in a following section, we argue information generated from these northern regions cannot be applied to southwestern forests: Forests in the desert Southwest carry comparatively large fractions of understory oak. Volatile chaparral fuels are also common in montane canyons of the desert Southwest. In contrast to the temperate rainforests of the Pacific Northwest, the arid climate of the desert Southwest produces in forested 'Sky Islands' extremely dry fine fuel beds and slow rates of fuel decomposition. In accord with these substantial differences, we believe fire prescriptions should be conservative, based on accurate assessments of fuel loads and topographic factors affecting fire spread, intensity and severity (Wright and Bailey 1982).

Data and Methods

Study Area

The Chiricahua Mountains are located in Cochise County of southeastern Arizona, 20 miles north of the U.S.-Mexico border, and 15 miles east of the Arizona-New Mexico border. The Chiricahua Mountain Wilderness is part of the Coronado National Forest, under USDA Forest Service management out of Douglas, Arizona. One of 40 in a sky island complex, otherwise known as the Madrean Archipelago, the Chiricahuas rise high above the Sonoran desert plain, supporting growth of a unique mixture of flora and fauna found in the Mexican Sierra Madre and U.S. Southern Rocky Mountains (Warshall 1994). The substantial biodiversity in the sky islands derives from their diverse geologic and paleoecologic history, and a geographic range spanning 3 climate zones (Warshall 1994).

Pole Bridge Canyon Research Natural Area spans 550 acres over an elevation range of 1800 - 2800 m at the central west side of the Chiricahua Mountains. Vegetation communities in PBCRNA range from oak-pine woodland at lower elevations to mixed-conifer forest at upper elevations. Pole Bridge Canyon was designated a Research Natural Area (RNA) in the 1930s or 40s. Areas given RNA status must be managed to preserve 'natural' conditions and are reserved for research purposes (USDA Forest Service, FS-503). The distinctive status of PBCRNA provides a unique opportunity to investigate the current state of forest vegetation influenced by a history of logging, grazing and fire.

Field Data Collection

Field data collected included the amount of downed woody fuels, stature of the overstory canopy; composition, density and size distribution of forest stands; topographic pose, and geographic locations. Fieldwork spanned 2 summers. Eleven sites were sampled May through July 1997. Sampling protocols were streamlined, and an additional 22 plots were sampled during late May and June 1998.

Using cluster analysis, we identified 6 distinctive combinations of spectral response patterns from Landsat TM and topographic data. These clusters were used to guide field sample site selection, insuring sites represented the full range of topographic, forest composition and structure variations (Medler and Yool 1998). The number of sample plots per cluster was determined by proportion of cluster area to total study site area (Table 1).

Due to the complex topography of this canyon, many of the clusters disintegrated into very small areas. Since field data must be accurately geo-registered to the digital databases to achieve valid geographic analysis, only large areas of contiguous cells for each cluster were selected for locating sample plots. This strategy ensured sampled plots were anchored geographically tc a specific cluster.

We recorded at each sample plot its GPS coordinates, topography, vegetation, fuel loads, slope and aspect. Average duff and litter depth were sampled, and down woody fuels were tallied by fuel moisture time lag classes to estimate of fuel loads (Brown 1982). Photographs were taken at each site. These data were compiled into a representative fire behavior fuel model (Anderson 1982). To assess structural variations, we recorded for each plot the average tree height and height to live crown of the 5 most representative trees. Canopy cover was estimated using ocular estimates and a densiometer. Total number of live or dead trees > 2.5 m was tallied. The diameter-at-breast-height (DBH) and genus/species was collected for all trees live or dead > 2.5 m tall. Relative stand density, total basal area, basal area density, and the proportion of total stems for each genus were also computed.

Our objectives here were to use these field compilations to characterize the spatial complexity of the fuel complex and to investigate the viability of commercial digital data products as proxies for fuel loads. We used a variety of methods to examine interactions between fuel load, stand density, basal area, community composition, topography, and TM spectral response. Simple linear regression was used to examine the strength and predictability of relationships between various combinations of TM spectral bands and total downed woody fuel loads. Regression and correlation analyses were used to examine the relationships between all variables.

Results and Discussion

Total downed woody fuel load for all sample sites exhibited a broad range of variability (6.21 ton/ha to 48.85 ton/ha), with average of 18.46 ton/ha, a standard deviation of 9.04 and a coefficient of variation of 48.97 (Tables 2,3). Correlation analyses revealed total downed woody fuel loads were most strongly correlated with a combination of TM bands 1,2,3 and slope, elevation and aspect (R = 0.70). Another noteworthy relationship included TM bands 1,2,3, elevation and aspect (R = 0.68). Adding TM bands 4 and 5 increased this correlation only slightly (R= 0.69). Elevation was highly positively correlated with the relative proportion of *Pseudotsuga menzesii* (R = 0.74; Figure 2). We saw strong relationships between duff and litter depths (R = 0.79), total basal area and basal area density (R= .084) and tree genus proportions (-0.83 between *Pinus* and *Pseudotsuga*, -0.80 between *Pseudotsuga* and *Quercus*). There is also strong relationship between *Quercus* and elevation (-0.77; Table 4; Figure 2). Remaining large R values (>0.70) are due to co-linearity among spectral bands. All other R values are less than 0.70 (Table 4). Linear regression of several combinations of spectral and topographic variables against total downed woody fuel load yields a modest adjusted R-squared value of 0.37 (Table 5).

Down and dead woody fuel loads in PBCRNA appear similar to those found in other montane canyons of southern Arizona and Mexico (Table 6). Escobedo (1998) computed fuel loads from an area north of PBCRNA in the Chiricahuas, with a similar average fine fuel load and total fuel load to PBCRNA. Sites in the Huachuca Mountains carry lower fuel loads in general. Conifer sites in the Garden Canyon watershed of the Huachuca mountains have much lower fine fuel loadings but greater coarse woody debris loads than in the Chiricahuas (Danzer, personal communication). Loads computed by Escobedo for study sites in the Huachucas are in general also less than those found in the Chiricahuas. Total downed woody fuel loads in the Huachuca and Chiricahua study sites are comparable. Higher fine fuel loads and lower coarse fuel loads in PBCRNA may be attributed to greater management restrictions for RNA's than non-RNA national forest land where logging, and grazing are permitted. Logging and fire have been excluded from PBCRNA since at least the mid 1900's.

Graphical analysis reveals trends where high and low fuel loads occur (for example, Figure 4). Extreme fuel loads are defined as those greater than one standard deviation above the mean fuel load for all sites. Based on this rule, 11 sites were identified with extreme fine fuel loads (1, 10, or 100 hour fuels). Of those 11 sites, 8 have slopes greater than 51%, 10 occur on northwesterly to northeasterly aspects, and 7 exceed 2100 meters in elevation. We defined low fuel loads as those greater than one standard deviation below the mean fuel loads for all sites. Another 11 sites were identified with low fuel loads at 1, 10, or 100-hour classes. Of those 11, 7 have slopes less than 51%, 5 occur on west facing slopes, 5 on northwest facing slopes, and 1 on a southern slope, and 9 occur under 2300 meters and 5 of those under 2200 meters

Conclusion and Limitations

This case study presents one example of the spatial variability of fuels in montane canyons of southern Arizona. We have in the course of this work collected high-resolution ground fuels data, characterized canopy properties, and tested the ability of commercial digital data to model fuel-topography relationships. Results show in general higher fuel loads can be found on steeper slopes, which tend to occur at highest elevations (>2000 m), and on northerly aspects. Stand composition at these locations tends to be primarily mixed conifer. Relationships between variables measured here reveal only modest trends between digital topographic variables, spectral variables and fuel loads.

There are several reasons for these results. First and foremost, fuels likely vary at much finer scales than represented by a 30 meter TM and DEM pixels. Thus the modeling of fuel properties a) is impaired by the comparatively coarse resolution of current commercial databases; but b) could be facilitated by the next generation of high-resolution remote sensors. Second, despite great care there are inevitable misregistration errors between the field and digital databases. We believe registration errors were minor.

The most salient outcome of this research is a quantitative appreciation for fuel complexity in montane canyons of the desert Southwest. Out of this observed complexity we believe a mandate emerges for extended field studies of fuels in the Southwest. Because these fuels are so distinctive regionally, we suggest they do not fit well into the current national fuel model classification scheme (i.e., Anderson 1982). These fuels are typically drier, vary at finer spatial scales and, due to the steep gradients of temperature and moisture found in these distinctive sky island forests, are usually more diverse than in the intermountain West, Pacific Northwest, or California. What lies ahead for fire-related research and resource management depends in part on the use we make of emerging high-resolution digital imaging technology. Results reported here motivate further research into the complexity of forest fuels in the desert Southwest, with the potential to inform forest management about what can and cannot be done with fire prescription here.

Acknowledgements

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Tables

Table 1: Allotment of sampling plots per topographic/spectral cluster.

	Prop. of total area	**# plots**
Cluster 1	.23	8
Cluster 2	.13	4
Cluster 3	.12	4
Cluster 4	.18	6
Cluster 5	.09	3
Cluster 6	.25	8
Total	1.0	33

Table 2: Fuels loads in tons/acre for each study site.

	1 hour	10 hour	100 hour	1000 hour		
	0-0.25	0.25-1.0	1.0-3.0	>3.0		TOTAL
POINT						
1	1.31	2.93	10.67	2.07		16.97
2	1.80	7.33	7.79	5.09		22.01
3	1.83	4.40	4.80	7.75		18.77
4	4.13	11.92	14.46	4.84		35.35
5	4.63	9.04	22.89	12.30		48.85
6	4.04	7.33	4.45	2.32		18.14
7	3.86	7.94	8.90	4.60		25.31
8	3.64	9.47	6.68	6.60		26.39
9	1.97	9.54	7.15	1.79		20.45
10	4.57	8.08	5.52	0.00		18.16
11	2.57	13.79	4.43	4.53		25.32
12	0.24	7.57	4.60	1.04		13.45
13	1.32	0.92	0.00	9.16		11.40
14	1.45	7.33	15.02	3.03		26.83
15	11.73	0.84	4.60	2.78		19.95
16	0.48	0.84	0.00	5.39		6.71
17	4.35	2.75	15.02	0.00		22.12
18	2.24	4.58	20.03	0.00		26.85
19	0.97	1.68	9.19	4.74		16.58
20	1.19	1.50	4.10	0.00		6.79
21	3.73	4.87	0.00	1.17		9.77
22	1.93	5.05	13.79	0.00		20.77
23	2.78	1.76	9.60	0.00		14.14
24	0.36	1.68	13.79	5.39		21.22
25	1.01	1.76	19.21	2.54		24.52
26	4.29	1.76	9.60	1.45		17.11
27	6.58	2.64	0.00	3.99		13.22
28	1.24	5.47	12.80	0.00		19.51
29	5.08	2.52	0.00	0.00		7.60
30	1.05	3.67	10.01	0.00		14.73
31	2.53	1.76	0.00	3.09		7.37
32	1.93	0.00	4.60	0.00		6.53
33	2.30	2.52	0.00	1.39		6.21
TOTAL	93.13	155.24	263.69	97.05		609.12
Average	2.82	4.70	7.99	2.94		18.46
StDev	2.24	3.55	6.33	3.03		9.04
CV	79.21	75.39	79.24	102.92		48.97

Table 3: Mean, Standard Deviation, and Coefficient of Variation for variables at 33 study plots.

Measured Variable	Mean	StDev	CV
1_HOUR (ton/ac)	2.82	2.24	79.21
10_HOUR (ton/ac)	4.70	3.55	75.39
100_HOUR (ton/ac)	7.99	6.33	79.24
1000_HOUR (ton/ac)	2.94	3.03	102.92
TOTALDWF (ton/ac)	18.46	9.04	48.98
LITTER (ton/ac)	1.36	0.61	44.50
DUFF (ton/ac)	1.11	0.83	74.49
MEAN_DBH (cm)	14.38	3.68	25.58
TOTAL_BA (m^2)	5.66	5.94	104.97
TOTAL_BAD (m^2/ ac)	38.89	13.16	33.83
DENSITY_(stems/ac)	1823.83	832.14	45.63
TREE_HEIGHT (m)	14.78	6.16	41.67
CROWN_HEIGHT (m)	5.96	4.43	74.32
ARBUTUS (proportion of total stems >2.5m tall)	0.00	0.01	256.06
CERCOCARPUS (proportion of total stems >2.5m tall)	0.00	0.02	399.80
DEAD (proportion of total stems >2.5m tall)	0.07	0.05	62.98
JUNIPERUS (proportion of total stems >2.5m tall)	0.00	0.01	340.77
PINUS (proportion of total stems >2.5m tall)	0.27	0.22	82.53
PSEUDOTSUGA (proportion of total stems >2.5m tall)	0.24	0.21	85.91
QUERCUS (proportion of total stems >2.5m tall)	0.41	0.32	78.95
SLOPE (percent) DEM 3x3 average	49.70	14.66	29.50
ELEVATION (m) DEM 3x3 average	2223.82	158.56	7.13
ASPECT (degrees) DEM 3x3 average	197.55	128.70	65.15
SLOPE (percent) Field Average	56	13.94	24.90
Elevation (m) Field Average	2222.87	185.64	8.35
Aspect (degrees) Field Average	163.21	114.92	70.41

Table 5: Results of linear regression analyses.

Dependent Variable	Independent Variables (3x3)	R	R-squared	Adjusted R-squared
total downed woody fuels (TDWF)	TM bands 1-5 & 7	0.58	0.34	0.19
TDWF	TM 1,2,3	0.56	0.32	0.25
TDWF	TM 2,3,4	0.43	0.18	0.096
TDWF	TM 3,4,5	0.51	0.26	0.15
TDWF	TM 1,2,3,4	0.56	0.34	0.19
TDWF	Kauth Thomas 1,2,3	0.46	0.21	0.13
TDWF	slope, elevation, aspect, TM 1,2,3	0.70	0.49	0.37
TDWF	elevation, aspect, TM 1,2,3	0.68	0.47	0.37
TDWF	elevation, aspect, TM 1,2,3,4,5	0.69	0.47	0.33

(TM and DEM pixel values used for regression and correlation analyses included 3x3 and 5x5 averages of pixels surrounding the geographic position of each field plot to ensure site specific field data was compared to corresponding digital pixels. Included here are results from 3x3 pixel average. Results using 5x5 pixel average were nearly identical.)

Table 6: Fuel load comparison between study sites in several southern Arizona mountain ranges.

	Danzer et al (Huachucas) Conifer/OakWood	Escobedo (Huachucas; Upper Sawmill/McClure)	Escobedo (Chiricahuas)	Beussink & Yool (Chiricahuas)
1 Hour (0.00-0.25")	0.20/1.09	0.15/0.25	0.72	2.82
10 Hour (0.25-1.00")	0.85/2.55	0.15/0.25	0.72	4.70
100 Hour (1.00-3.00")	2.15/1.01	--	--	7.99
Mean Fine Fuels(0.00-3.00")	1.05/1.53	2.95/1.95	4.20	5.17
1000 Hour (>3.0")	17.25/1.30	9.5/8.5	15.9	2.94
TOTAL	20.65/6.60	13.0/10.0	22.00	18.46
Duff	14.45	--	--	1.11

Figure 1: Stand composition by site in order of increasing slope.

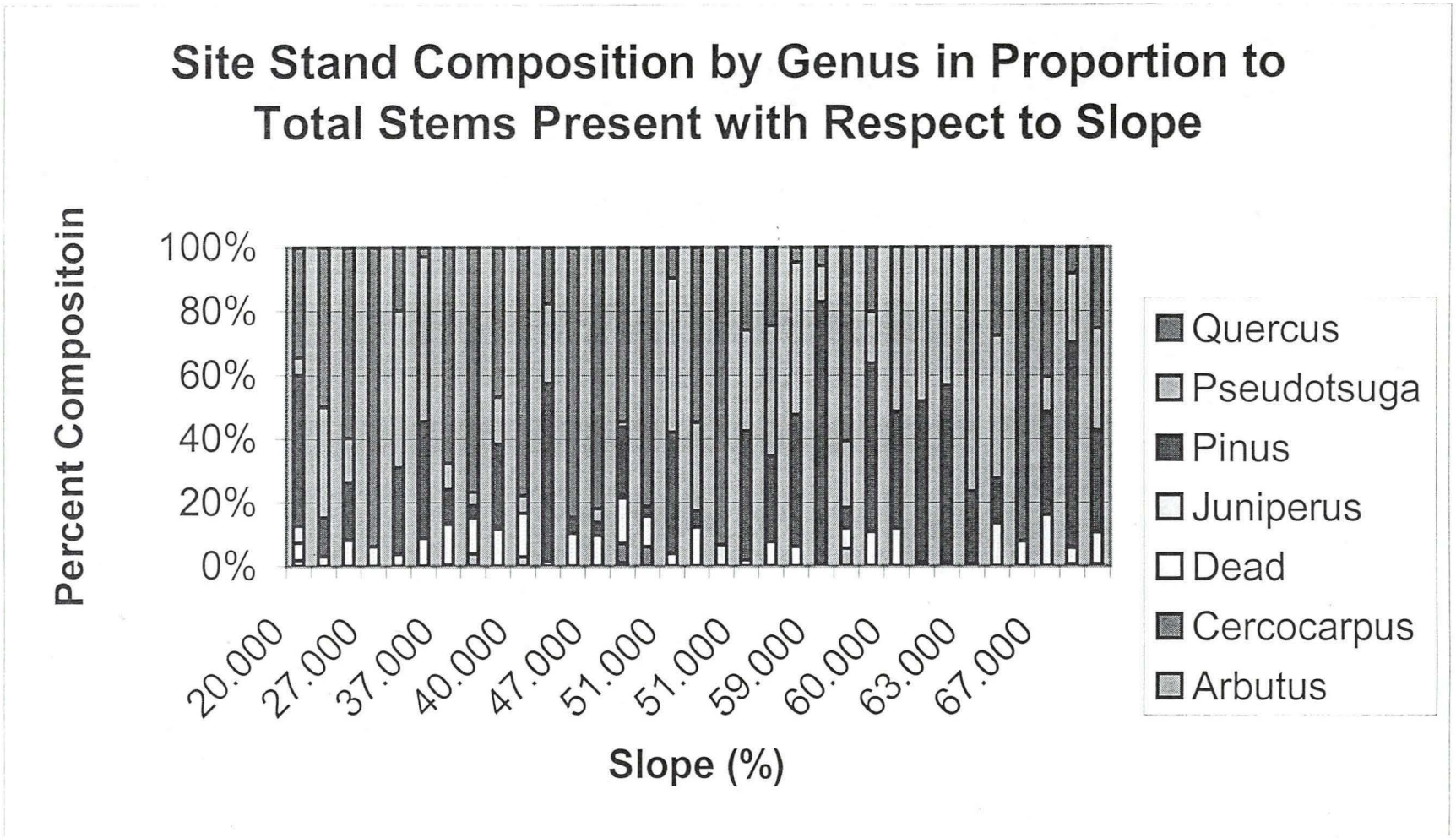


Figure 2: Stand Composition by site in order of increasing elevation.

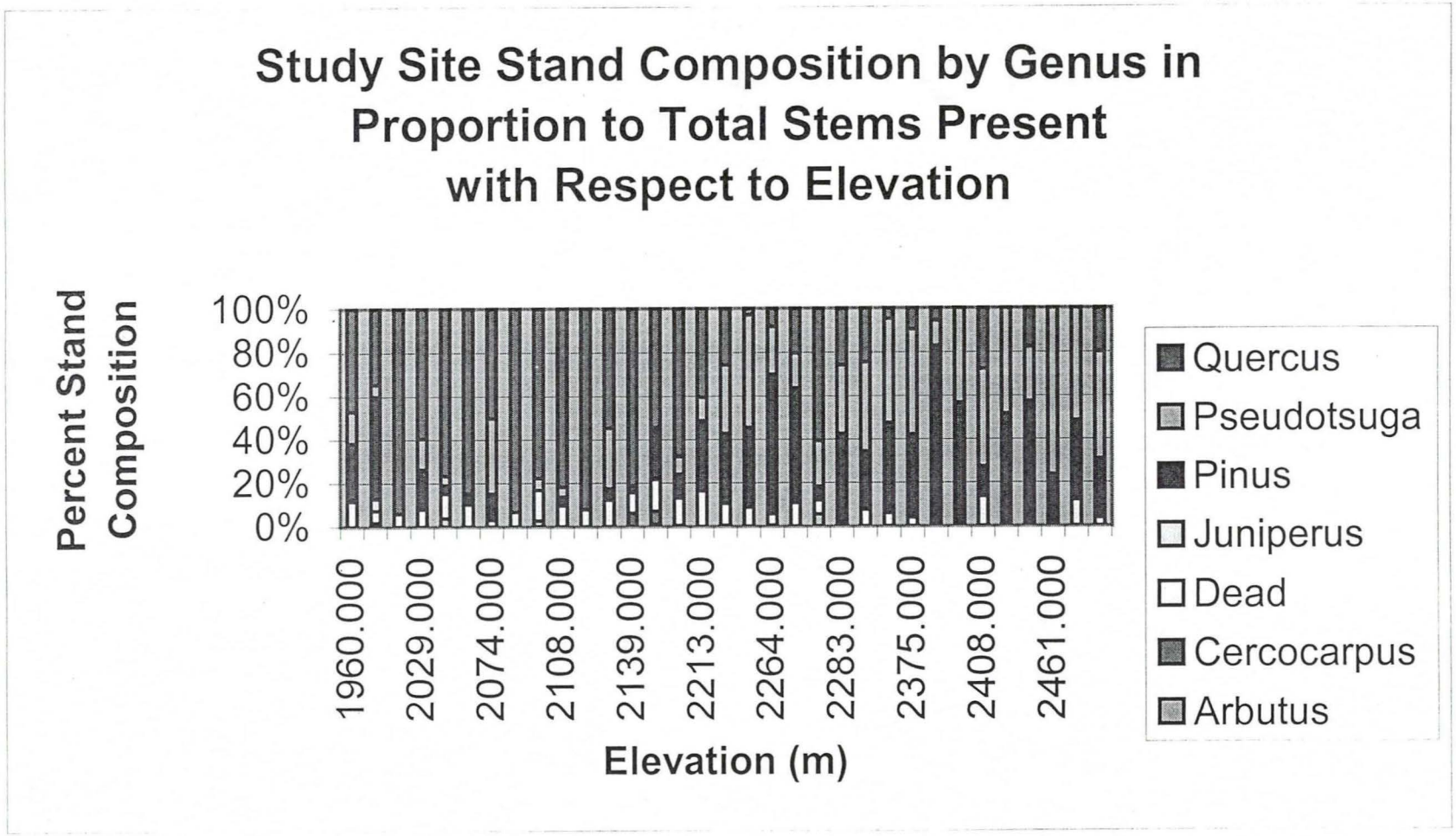


Figure 3: Stand composition by site in order of increasing aspect.

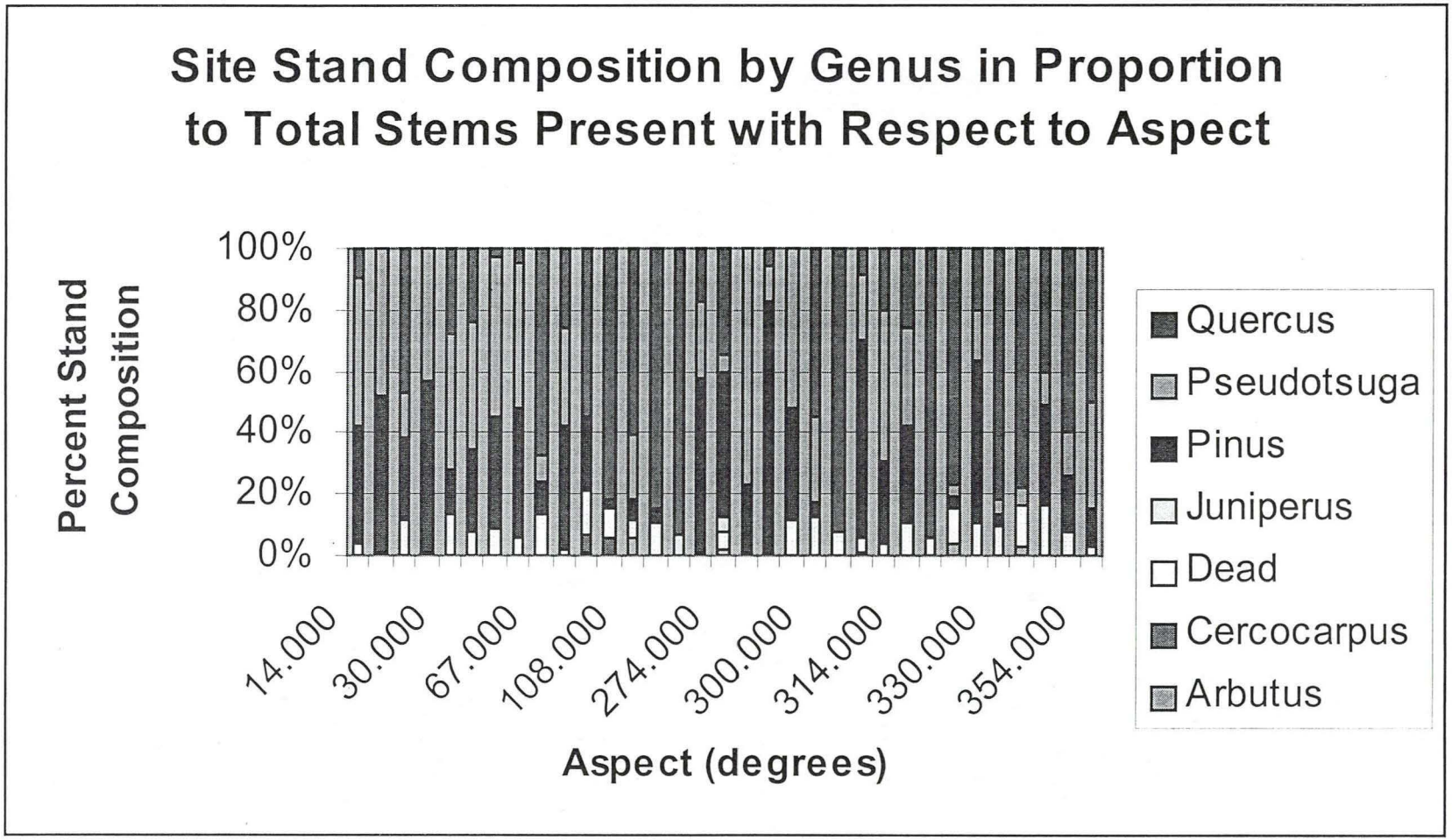
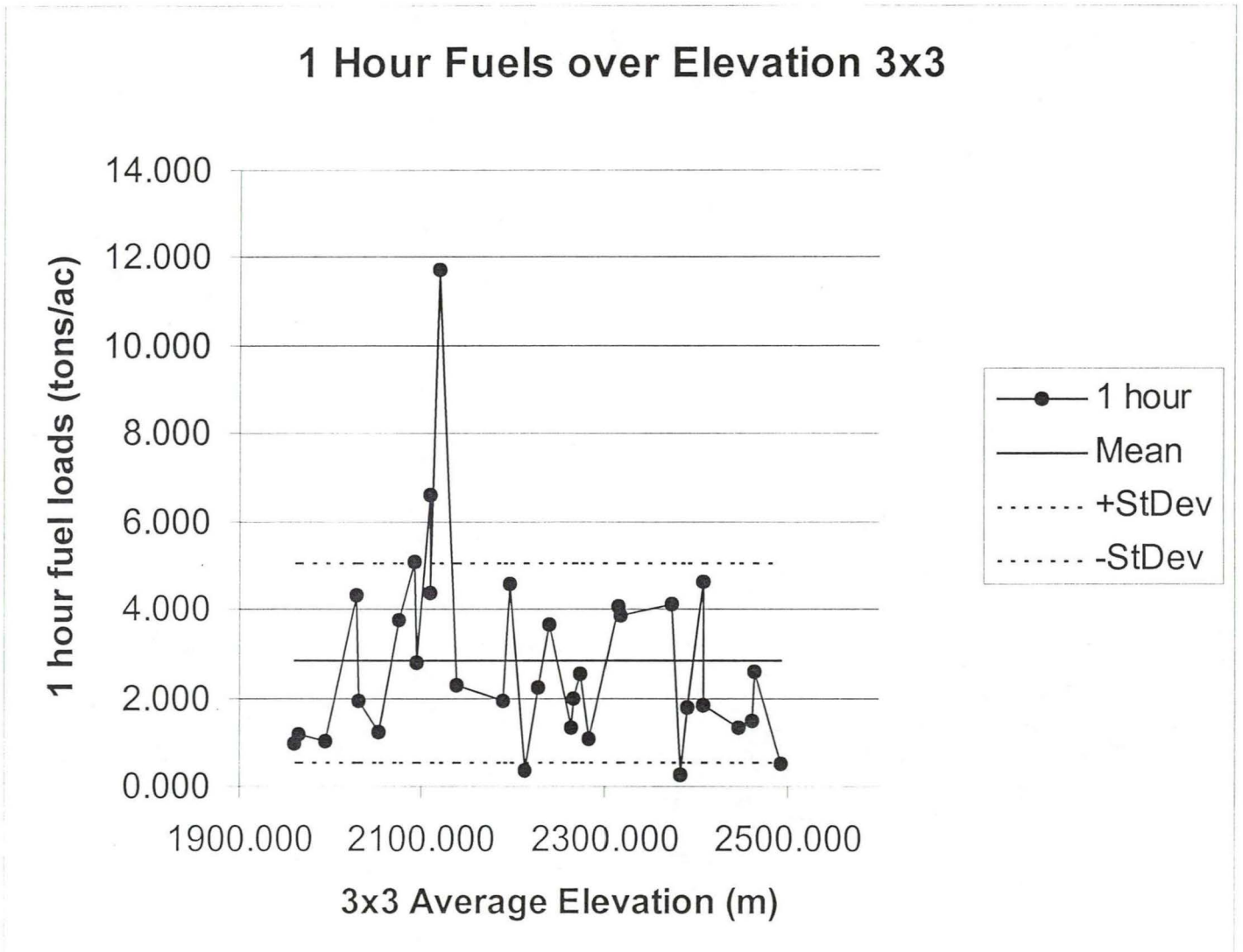


Figure 4: Variation in one hour fuels over elevation.



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Abstract

Pole Bridge Canyon is a Research Natural Area and representative montane canyon in the Chiricahua Mountains of Southeastern Arizona. Montane canyons of the Southwest are oases for diverse flora and fauna, and are subject to wildfire. We combine a digital elevation model, fine-scale field data and remotely sensed imagery to examine fuel load complexities among distinctive vegetation types and topographic positions. Digital elevation models (DEM) provide the topographic distributions, representing temperature and precipitation variations that affect fuel production. DEM data and in situ measurements of surface fuels and forest composition and structure are used to characterize overall fuel complexity. Multispectral remote sensor data from Landsat Thematic Mapper (TM) data provide spectral information on forest structure and

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Keywords: forest fuels, topography, GIS, fire, management, southwest, Arizona, sky island, Landsat Thematic Mapper, TM

Introduction

Montane canyons of the desert Southwest support diverse floras, including many endangered species. These canyons serve also as corridors of fire spread, capable of destroying their own resources while moving fire into upper elevation forests. Spatially explicit, quantitative studies of fuels variations in the montane canyons that characterize the Southwestern U.S. should lead to more accurate formulations of potential fire behavior and informed management decisions. We describe in this article the distribution of fuel loads and forest structural characteristics as related to topography, vegetation community and multi-spectral remote sensor data. Our 3 technical aims were to 1) obtain high-resolution ground fuels data; 2) characterize forest composition and structure; 3) test the viability of commercial digital databases for fuels modeling. Our research was conducted in Pole Bridge Canyon Research Natural Area (PBCRNA), a representative montane canyon in the Chiricahua Wilderness of Southeastern Arizona. Our approach combines GIS, remote sensing, and field data collections to characterize fuel loads.

There is a clear and present need for fire research associated with prescribed burning, leading to reduced fuel loads in the Southwest (Ffolliott 1996). Results from this study demonstrate relations between forest fuel loads and topography are complex. In light of observed complexity, we claim fuel reduction techniques, specifically prescribed fire, should not be implemented in montane forests of southern Arizona using current classification schemes.

Following brief Background on the fire history of the region and the uniqueness of Southern Arizona fuel complexes, we describe in Data and Methods our field site and data collection methods. The Results and Discussion section presents an analysis of relationships between fuel loads, topographic positions, and forest characteristics. We conclude with a summary of salient findings, study limitations, and recommendations.

Background

Regional Fire History

Fire regime changes in this region have included shifts in forest structure (Cooper 1926; Cooper 1960; Stein 1988; Fule, et al. 1997), and lengthened fire frequency intervals (Swetnam and Baisan1996). These changes have increased fuel loads (Allen 1996) generally in the Southwest, and specifically in the Chiricahua Mountains of southeastern Arizona (Sawyer and Kinraide 1980; Swetnam and Baisan 1996). Fire suppression in the Chiricahuas has eliminated the frequent low intensity fires that maintained historically light fuel loads (Swetnam 1988; Allen 1996; Swetnam and Baisan 1996). Large, costly fires have resulted, altering these suppressed forests and their natural processes (Picket and White 1985; Agee 1993). The Rattlesnake fire, for example, burned 26,000 acres in summer 1994 --one third of the Chiricahua Wilderness (Allen 1994; Hardy 1998). For perspective, the amount of energy released by fires of this size is on the order of 3×10^{12} British Thermal Units (BTUs), equivalent to 90 thunderstorms or 9 times the energy released by the Hiroshima atomic bomb (Pyne 1996). The Clark Peak Fire on Mt. Graham, Arizona burned about 6500 acres in spring 1996, coming within 200 meters of the Mt. Graham International Observatory. Resources brought to this fire

included 1100 persons, 26 engines and 9 helicopters. More recently, in May 2000 wildfires near Los Alamos, New Mexico burned over 47000 acres, destroying 235 homes and many other structures, including portions of Los Alamos National Laboratories (National Interagency Fire Center, 2000). Such events compel fuels mapping and new management initiatives to prevent destructive wildfire. A new fire management plan has been proposed for part of the Wilderness not affected by the Rattlesnake fire. This plan aims to reduce high fuel loads that threaten the Chiricahua Wilderness with catastrophic wildfire (Hardy 1998).

Unique Southwest Fuel Complexes

Prescribed natural fire is increasingly adopted as a means of restoring natural fire regimes to systems with a history of grazing, logging, and fire suppression (Ffolliott, et al., 1996; Sackett, et. al, 1996; USDI, USDA 1996). Restoring natural fire cycles to systems no longer natural appears, however, improbable (Allen 1994; Fflolliot 1996). Prior fire research focused primarily on the timber regions of the Rocky Mountains and Pacific Northwest. Southwest forests carry a comparatively large understory of oak (Figure 1). Volatile chaparral fuels (e.g., *Cercocarpus*, *Ceanothus and Rhus* spp.) are also common in montane canyons of the Southwest. In contrast to the temperate rainforests of the Pacific Northwest, the arid climate and rugged topography of the desert Southwest produces in forested 'Sky Islands' extremely dry fine fuel beds and slow rates of fuel decomposition. In accord with these substantial differences, we believe fire prescriptions, if used at all, should be conservative, based on fine-scale assessments of fuel loads and topographic factors affecting fire spread, intensity and severity (Wright and Bailey 1982).

Data and Methods

Study Area

The Chiricahua Mountains are located in Cochise County of southeastern Arizona, 20 miles north of the U.S.-Mexico border, and 15 miles west of the Arizona-New Mexico border. The Chiricahua Mountain Wilderness is part of the Coronado National Forest, under USDA Forest Service management out of Douglas, Arizona. One of 40 in a sky island complex, otherwise known as the Madrean Archipelago, the Chiricahuas rise abruptly above the Sonoran desert plain, supporting a unique flora and fauna found in the Mexican Sierra Madre and U.S. Southern Rocky Mountains (Warshall 1994). Substantial biodiversity in the sky islands derives from their diverse geologic and paleoecologic history, and a geographic range spanning 3 climate zones (Warshall 1994).

Pole Bridge Canyon Research Natural Area, one of two Coronado National Forest RNA's, spans 550 acres over an elevation range of 1800 - 2800 m on the west side of the Chiricahua Mountains. Vegetation communities in PBCRNA range from oak-pine woodland at lower elevations to mixed-conifer forest at upper elevations. Areas given RNA status must be managed to preserve 'natural' conditions and are reserved for research purposes (USDA Forest Service, 1992). The distinctive status of PBCRNA provides a unique opportunity to investigate the current state of forest vegetation influenced by a history of logging, grazing and fire.

Field Data Collection

Field data collected included the amount of downed woody fuels, stature of the overstory canopy; composition, density and size distribution of forest stands; topographic pose, and global positioning system (GPS) locations. Thirty-three sites were sampled in summer 1997 and summer 1998.

Using cluster analysis, we identified 6 distinctive combinations of spectral response patterns from Landsat TM bands 3,4, & 5, and topographic diversity (full range of slope, elevation and aspect from a DEM). The TM bands selected are sensitive to color (TM 3, 0.63-0.69 μm, structure (TM, 0.76-0.90 μm) and internal moisture (TM 5, 1.55-1.75 μm) differences among different types of vegetation (Jensen 2000). These clusters were used to guide field sample site selection, insuring sites represented the full range of topographic, forest composition and structure variations (Medler and Yool 1998). The number of sample plots per cluster was determined by proportion of cluster area to total study site area (Table 1).

Due to the complex topography of this canyon, many of the clusters disintegrated into very small areas, often isolated pixels. Because field data must be accurately geo-registered to the digital databases for valid geographic analysis, only large areas of contiguous same-cluster cells were selected for locating sample plots. This strategy ensured sampled plots were anchored geographically to a specific cluster.

We recorded at each sample plot GPS coordinates, topography, vegetation, fuel loads, slope and aspect. Average duff and litter depth were sampled, and downed woody

fuels were tallied by fuel moisture time lag classes to estimate fuel loads (Brown 1982). Photographs were taken at each site. These data were compiled into a representative fire behavior fuel model (Anderson 1982). To assess structural variations, we recorded for each plot the average tree height and height to live crown of the 5 most representative trees. Canopy cover was estimated using ocular estimates and a densiometer. Total number of live or dead trees > 2.5 m was tallied. The diameter-at-breast-height (DBH) and genus/species was collected for all trees live or dead > 2.5 m tall. Relative stand density, total basal area, basal area density, and the proportion of total stems for each genus were also computed.

We used a variety of methods to examine interactions between fuel loads, stand density, basal area, community composition, topography, and TM spectral response. Simple linear regression was used to examine the strength and predictability of relationships between various combinations of TM spectral bands and total downed woody fuel loads. Regression and correlation analyses were used to examine the relationships between all variables. Multi-variate regression tested for more complex interactions.

Results and Discussion

Total downed woody fuel load for all sample sites exhibited a broad range of variability (6.21 ton/ha to 48.85 ton/ha), with average of 18.46 ton/ha, a standard deviation of 9.04 and a coefficient of variation of 48.97 (Tables 2, 3). Regression analyses (Table 4) revealed total downed woody fuel loads were most strongly predicted

by a combination of TM bands 1,2,3 and slope, elevation and aspect (R = 0.70). Another noteworthy relationship included TM bands 1,2,3, elevation and aspect (R = 0.68). Adding TM bands 4 and 5 increased this predictability only slightly (R= 0.69). Correlation analyses (Table 5) revealed elevation was positively correlated with the relative proportion of Pseudotsuga menzesii (R = 0.74). We saw strong relationships between duff and litter depths (R = 0.79), total basal area and basal area density (R= 0.84) and tree genus proportions (-0.83 between Pinus and Pseudotsuga, -0.80 between Pseudotsuga and Quercus). There is also strong relationship between Quercus and elevation (-0.77). Remaining large R values (>0.70) are due to co-linearity among spectral bands. All other R values are less than 0.70. Linear regression of several combinations of spectral and topographic variables against total downed woody fuel load yields a modest adjusted R-squared value of 0.37.

Downed woody fuel loads in PBCRNA appear similar to those found in other montane canyons of southern Arizona and Mexico (Table 6). Escobedo Montoya (1998) computed fuel loads from an area north of PBCRNA in the Chiricahuas, with a similar average fine fuel load and total fuel load to PBCRNA. Sites in the Huachuca Mountains carry lower fuel loads in general. Conifer sites in the Garden Canyon watershed of the Huachuca Mountains have much lower fine fuel loadings but greater coarse woody debris loads than in the Chiricahuas (Danzer, personal communication). Loads computed by Escobedo Montoya for study sites in the Huachucas are in general also less than those found in the Chiricahuas. Total downed woody fuel loads in the Huachuca and Chiricahua study sites are comparable. Higher fine fuel loads and lower coarse fuel loads

in PBCRNA may be attributed to greater management restrictions for RNA's than non-RNA national forest land where logging, and grazing are permitted. Logging and fire have been excluded from PBCRNA since at least the mid 1900's.

Graphical analysis reveals a few sites where high and low fuel loads occur (for example, Figure 2). Extreme fuel loads are defined as those greater than one standard deviation above the mean fuel load for all sites. Based on this rule, 11 sites were identified with extreme fine fuel loads (1, 10, or 100 hour fuels). Of those 11 sites, 8 have slopes greater than 51%, 10 occur on northwesterly to northeasterly aspects, and 7 are at an elevation above 2100 meters. Low fuel loads are defined as less than one standard deviation below the mean fuel loads for all sites. Another 11 sites were identified with low fuel loads at 1, 10, or 100-hour classes. Of those 11, 7 have slopes less than 51%, 5 occur on west facing slopes, 5 on northwest facing slopes, and 1 on a southern slope, and 9 occur under 2300 meters and 5 of those under 2200 meters

Conclusion and Limitations

This case study presents one example of the spatial variability of fuels in montane canyons of southern Arizona. We have in the course of this work collected high-resolution ground fuels data, characterized forest composition and structure, and tested the ability of commercial digital data to model fuel-topography relationships. Results show in general higher fuel loads can be found on steeper slopes, at higher elevations (>2000 m), and on northerly aspects. Stand composition at these locations tends to be

225 primarily mixed conifer. Relationships between variables measured here reveal modest
226 trends between digital topographic variables, spectral variables and fuel loads.
227
228 There are several reasons for these results. First, fuels likely vary at much finer
229 scales than represented by a 30 meter TM and DEM pixels. Thus the modeling of fuel
230 properties is impaired by the comparatively coarse resolution of current commercial
231 databases; but could be facilitated by the next generation of high-resolution remote
232 sensors. Second, despite great care there are inevitable mis-registration errors between
233 the field and digital databases. The root mean square error in geo-registering the TM
234 scene was +/- 30 meters; GPS error was estimated to be at most +/- 30 meters.
235 Averaging DEM and TM data by a 3 x 3 window and placing sample sites within areas of
236 contiguous same-cluster cells, helped to reduce the impact of these errors on our results.
237
238 The most salient outcome of this research is a quantitative appreciation for fuel
239 complexity in montane canyons of the desert Southwest. Out of this observed complexity
240 we believe a mandate emerges for extended field studies of fuels in the Southwest.
241 Because these fuels are so distinctive regionally, we suggest they do not fit well into the
242 current national fuel model classification scheme (i.e., Anderson 1982). These fuels are
243 typically drier, vary at finer spatial scales and, due to the steep gradients of temperature
244 and moisture found in these distinctive sky island forests, are usually more diverse than
245 in the intermountain West, Pacific Northwest, or California. What lies ahead for fire-
246 related research and resource management depends in part on the use we make of
247 emerging high-resolution digital imaging technology. Results reported here motivate

248 further research into the complexity of forest fuels in the desert Southwest, with the
249 potential to inform forest management about what can and cannot be done with
250 prescribed fire here.
251
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352 **Tables**

353

354 Table 1: Allotment of sampling plots per topographic/spectral cluster.

355

	Proportion of total area	Number of sample sites
Cluster 1	0.23	8
Cluster 2	0.13	4
Cluster 3	0.12	4
Cluster 4	0.18	6
Cluster 5	0.09	3
Cluster 6	0.25	8
Total	1.00	33

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357 Table 2: Computed fuels loads (tons/acre) for each study site.
358

	Time lag fuel moisture class				
	1 hour (0-0.25")	10 hour (0.25-1.0")	100 hour (1.0-3.0")	1000 hour (>3.0")	
Site					**Total**
1	1.31	2.93	10.67	2.07	16.97
2	1.80	7.33	7.79	5.09	22.01
3	1.83	4.40	4.80	7.75	18.77
4	4.13	11.92	14.46	4.84	35.35
5	4.63	9.04	22.89	12.30	48.85
6	4.04	7.33	4.45	2.32	18.14
7	3.86	7.94	8.90	4.60	25.31
8	3.64	9.47	6.68	6.60	26.39
9	1.97	9.54	7.15	1.79	20.45
10	4.57	8.08	5.52	0.00	18.16
11	2.57	13.79	4.43	4.53	25.32
12	0.24	7.57	4.60	1.04	13.45
13	1.32	0.92	0.00	9.16	11.40
14	1.45	7.33	15.02	3.03	26.83
15	11.73	0.84	4.60	2.78	19.95
16	0.48	0.84	0.00	5.39	6.71
17	4.35	2.75	15.02	0.00	22.12
18	2.24	4.58	20.03	0.00	26.85
19	0.97	1.68	9.19	4.74	16.58
20	1.19	1.50	4.10	0.00	6.79
21	3.73	4.87	0.00	1.17	9.77
22	1.93	5.05	13.79	0.00	20.77
23	2.78	1.76	9.60	0.00	14.14
24	0.36	1.68	13.79	5.39	21.22
25	1.01	1.76	19.21	2.54	24.52
26	4.29	1.76	9.60	1.45	17.11
27	6.58	2.64	0.00	3.99	13.22
28	1.24	5.47	12.80	0.00	19.51
29	5.08	2.52	0.00	0.00	7.60
30	1.05	3.67	10.01	0.00	14.73
31	2.53	1.76	0.00	3.09	7.37
32	1.93	0.00	4.60	0.00	6.53
33	2.30	2.52	0.00	1.39	6.21
Total	93.13	155.24	263.69	97.05	609.12
Average	2.82	4.70	7.99	2.94	18.46
St. Dev.	2.24	3.55	6.33	3.03	9.04
C.V.	79.21	75.39	79.24	102.92	48.97

Table 3: Mean, standard deviation, and coefficient of variation for variables measured at 33 study sites.

Measured Variable	Mean	St.Dev.	CV
1 hour (ton/ac)	2.82	2.24	79.21
10 hour (ton/ac)	4.70	3.55	75.39
100 hour (ton/ac)	7.99	6.33	79.24
1000 hour (ton/ac)	2.94	3.03	102.92
Total downed woody fuel (ton/ac)	18.46	9.04	48.98
Litter (ton/ac)	1.36	0.61	44.50
Duff (ton/ac)	1.11	0.83	74.49
Mean DBH (cm)	14.38	3.68	25.58
Total basal area (m^2)	5.66	5.94	104.97
Total basal area density (m^2/ ac)	38.89	13.16	33.83
Density (stems/ac)	1823.83	832.14	45.63
Tree height (m)	14.78	6.16	41.67
Crown height (m)	5.96	4.43	74.32
Arbutus [1]	0.00	0.01	256.06
Cercocarpus [1]	0.00	0.02	399.80
Dead [1]	0.07	0.05	62.98
Juniperus [1]	0.00	0.01	340.77
Pinus [1]	0.27	0.22	82.53
Pseudotsuga [1]	0.24	0.21	85.91
Quercus [1]	0.41	0.32	78.95
Slope (percent) [2]	49.70	14.66	29.50
Elevation (m) [2]	2223.82	158.56	7.13
Aspect (degrees) [2]	197.55	128.70	65.15
Slope (percent) [3]	56	13.94	24.90
Elevation (m) [3]	2222.87	185.64	8.35
Aspect (degrees) [3]	163.21	114.92	70.41

[1]Proportion of total stems >2.5m tall. [2] DEM 3x3 average. [3] Average field measurement.

364 Table 4: Results of linear regression analyses.

365

Dependent variable	Independent variables (3x3)	R	R-squared	Adjusted R-squared
Total downed woody fuels (TDWF)	TM bands 1-5 & 7	0.58	0.34	0.19
TDWF	TM 1,2,3	0.56	0.32	0.25
TDWF	TM 2,3,4	0.43	0.18	0.096
TDWF	TM 3,4,5	0.51	0.26	0.15
TDWF	TM 1,2,3,4	0.56	0.34	0.19
TDWF	Kauth Thomas 1,2,3	0.46	0.21	0.13
TDWF	slope, elevation, aspect, TM 1,2,3	0.70	0.49	0.37
TDWF	elevation, aspect, TM 1,2,3	0.68	0.47	0.37
TDWF	elevation, aspect, TM 1,2,3,4,5	0.69	0.47	0.33

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Table 5: Results of correlation analysis (R) between topographic variables measured from the DEM with a 3x3 average, and fuels and vegetation variables.

Measured Variable	Slope (%)	Elevation (m)	Aspect (°)
1 hour	-0.00	-0.18	-0.00
10 hour	0.26	0.50	-0.29
100 hour	0.22	0.01	-0.01
1000 hour	0.31	0.47	-0.28
Total downed woody fuel	0.36	0.32	-0.21
Litter	0.37	0.38	0.01
Duff	0.25	0.54	-0.14
Mean DBH	-0.14	0.20	0.15
Basal area (m^2)	0.22	0.47	-0.57
Basal area density (m^2/ac)	0.27	0.42	-0.39
Density (stems/ac)	0.33	-0.01	-0.31
Tree height	-0.11	0.18	-0.23
Crown height	0.17	-0.10	0.08
Arbutus	-0.11	-0.21	0.10
Cercocarpus	-0.04	-0.10	-0.19
Dead	0.00	-0.36	0.13
Juniperus	-0.24	-0.35	-0.05
Pinus	0.30	0.54	-0.11
Pseudotsuga	0.27	0.74	-0.26
Quercus	-0.36	-0.77	0.23
Slope	--	0.52	-0.14
Elevation	--	--	-0.26
Aspect	--	--	--

371 Table 6: Mean fuel load (ton/ac) comparison between study sites in several southern
372 Arizona mountain ranges.
373

Fuel class	Huachuca Mountains [1] (Garden Canyon; conifer/oak woodland)	Huachuca Mountains [2] (Upper Sawmill/ McClure)	Chiricahua Mountains [2] (El Tigre)	Chiricahua Mountains [3] (PBCRNA)
1 hour (0.00-0.25")	0.20/1.09	0.15/0.25	0.72	2.82
10 hour (0.25-1.00")	0.85/2.55	0.15/0.25	0.72	4.70
100 hour (1.00-3.00")	2.15/1.01	2.95/0.95	4.10	7.99
Mean fine fuels (0.00-3.00")	1.05/1.53	2.95/1.95	4.20	5.17
1000 hour (>3.0")	17.25/1.30	9.50/8.50	15.90	2.94
Total	20.65/6.60	13.00/10.00	22.00	18.46
Duff	14.45	--	--	1.11

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375 [1] Danzer, personal communication; [2] Escobedo Montoya, 1998; [3] Rollins & Yool.
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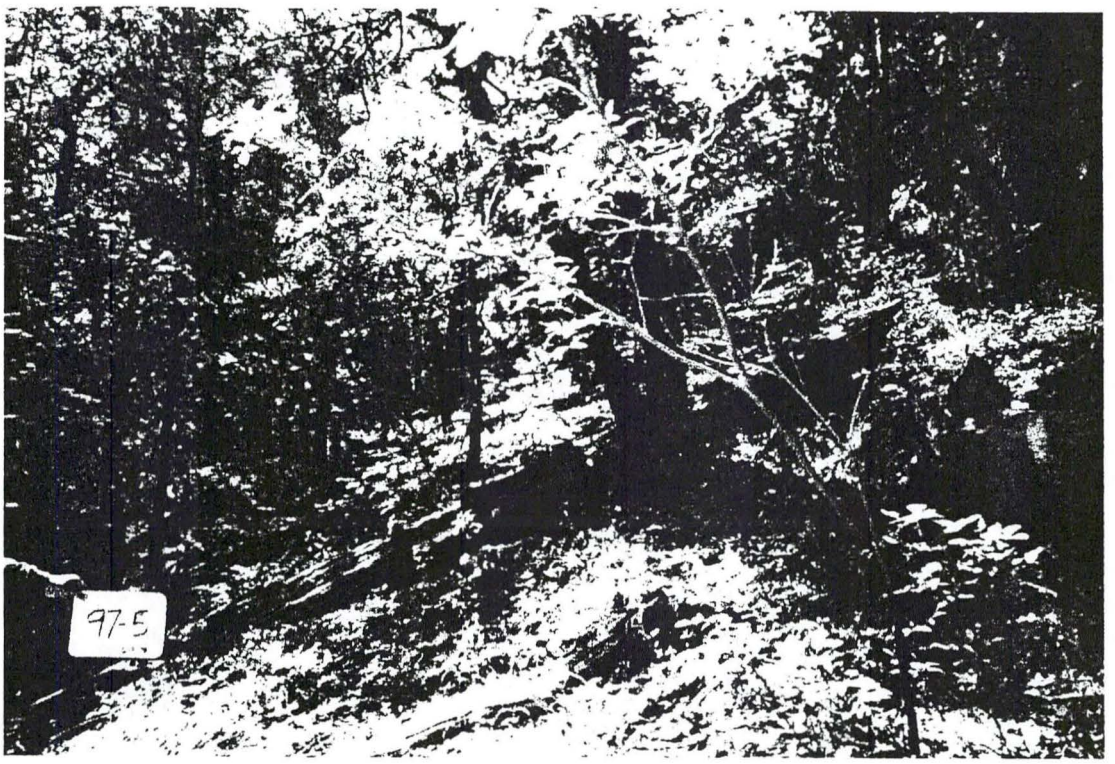
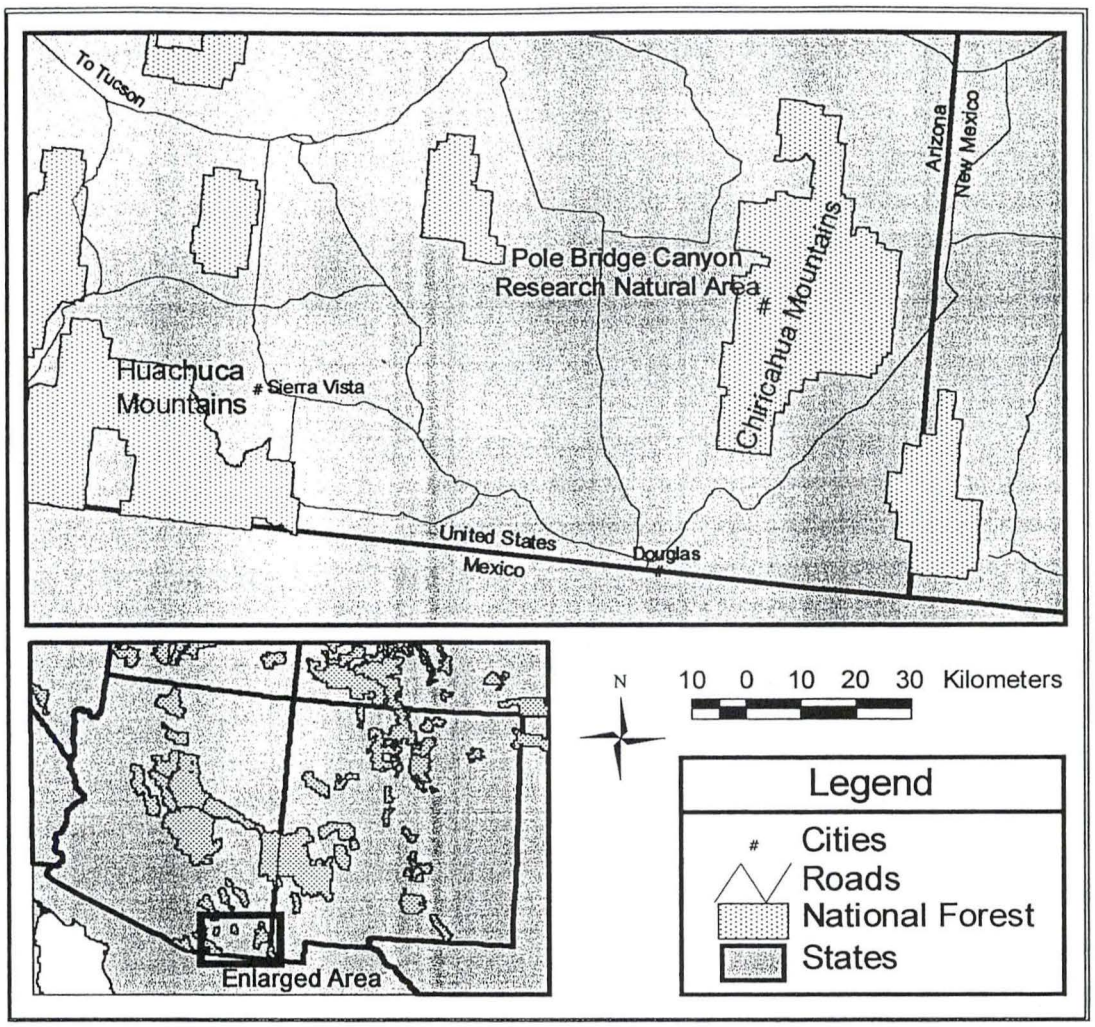


a.

b.

Figure 1: Study sites with high understory oak-fraction.



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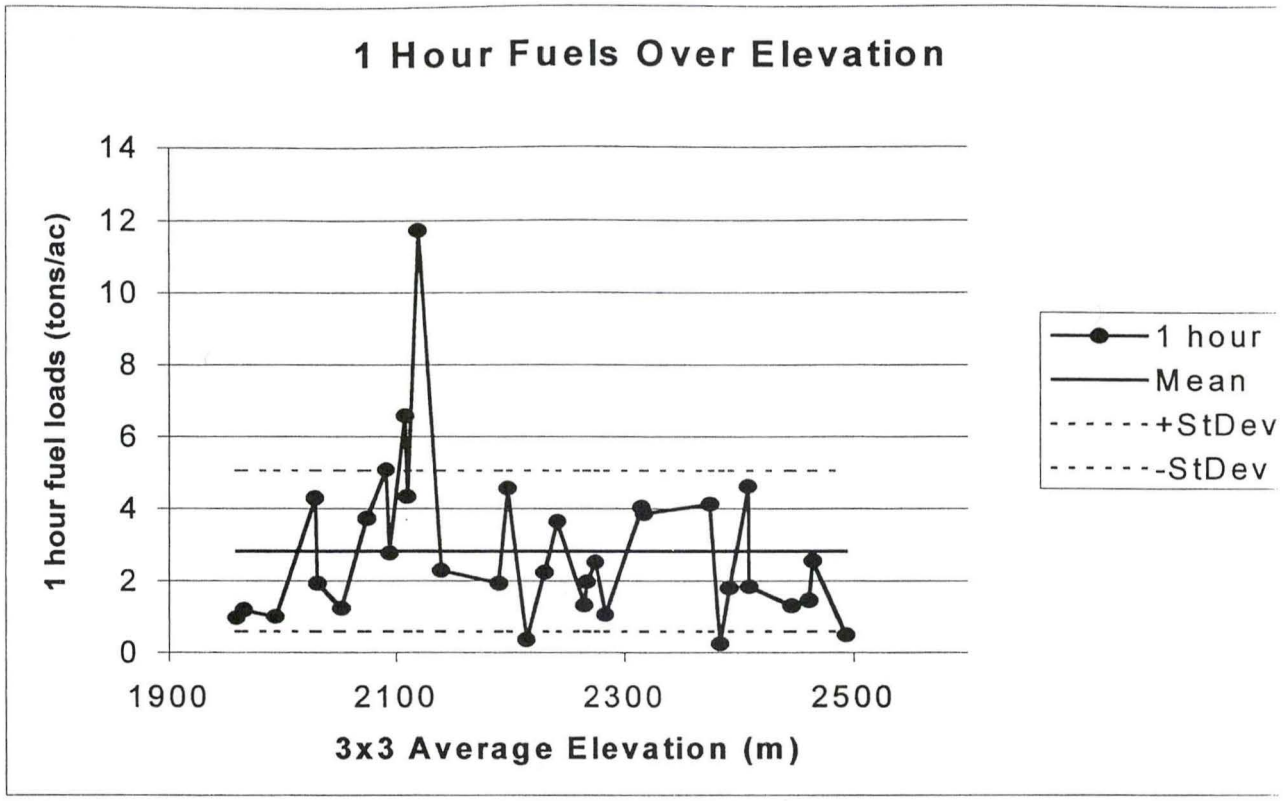
384 Figure 2: Location of Chiricahua Mountains relative to southeastern Arizona and
385 southwestern New Mexico.



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387 Figure 3: Variation in one-hour fuels over elevation.
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